

2.9 Lasing properties of THz quantum-cascade lasers

Quantum-cascade lasers (QCLs) for the THz spectral region, bridging the gap between optical emitters and electronic sources of radiation, are promising candidates for applications such as medical imaging in the THz regime. While pulsed lasing operation has recently been reported at temperatures somewhat above 100 K, the limiting processes for operation at higher temperatures have still to be investigated in more detail. Since existing THz QCLs require a rather complex design, an additional interesting subject is the question to what extent the structure of the cascade can be simplified, in particular, whether or not a conventional superlattice can supply sufficient gain for lasing operation.

First, two existing designs for GaAs/Al_{0.15}Ga_{0.85}As QCLs which operate in the THz spectral region were grown, processed, and investigated. Structure I [S. Barbieri *et al.*, Appl. Phys. Lett. **85**, 1674 (2004)] contains 90 periods each with 18 layers, while structure II [R. Köhler *et al.*, Nature **417**, 156 (2002)] consists of 104 periods each with 14 layers. The samples were grown by molecular-beam epitaxy on GaAs substrates. A challenge is the determination of the appropriate doping density for lasing operation. Therefore, a series of QCL structures with a reduced number of periods (15 periods) and various doping densities were fabricated and characterized. Probably due to the low Al content of the barriers, the current density is significantly more sensitive to the doping level than for mid-infrared QCLs.

For THz lasers, the optical confinement is usually achieved by the upper metallic contact layer and a heavily doped GaAs layer between the cascade and the substrate. In order to reduce the optical losses due to free-carrier absorption within the substrate, semi-insulating GaAs wafers have to be used. Therefore, both contacts are required to be on top of the wafer so that the etching process has to be stopped precisely at the lower contact layer, which is about 0.8 μm thick. The etching depth corresponds to the total thickness of the QCL structure of about 10 μm . The typical dimensions of the laser stripe are $200 \times 4000 \mu\text{m}^2$.

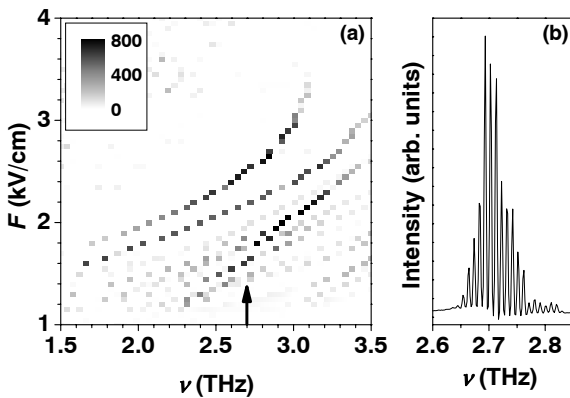


Fig. 23. (a) Calculated gain coefficient in arbitrary units as a function of electric-field strength F and frequency ν for structure I. (b) Lasing spectrum at 7 K.

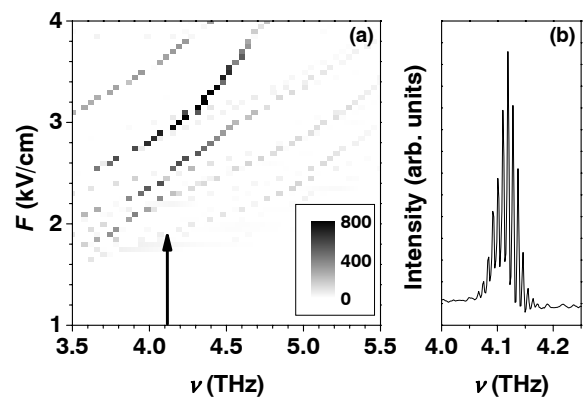


Fig. 24. (a) Calculated gain coefficient in arbitrary units as a function of electric-field strength F and frequency ν for structure II. (b) Lasing spectrum at 7 K.

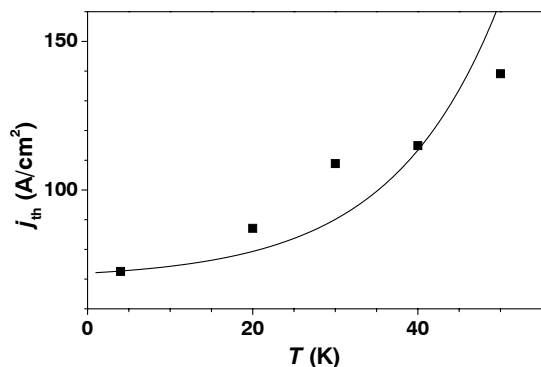


Fig. 25. Threshold current density as a function of the operating temperature for structure I. The exponential fit (solid line) serves as a guide to the eye.

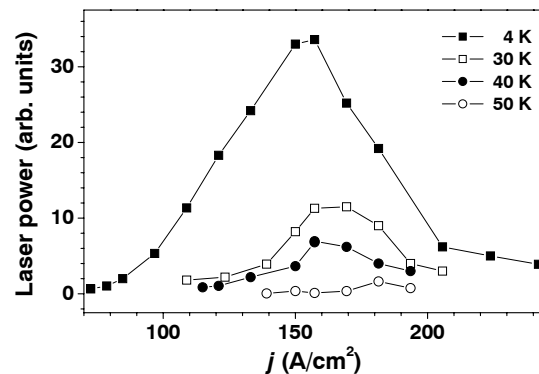


Fig. 26. Laser power output as a function of current density measured for structure I at several temperatures between 4 and 50 K.

For a comparison of various structures, the gain coefficient is calculated in the framework of the self-consistent solution of the Schrödinger and Poisson equations using a scattering-rate approach for vanishing in-plane wave vector. The calculated gain coefficients as shown for structure I in Fig. 23(a) and for structure II in Fig. 24(a) exhibit a rather large gain at transition frequencies in the range of 2.5–3.0 THz and 3.9–4.4 THz, respectively. The lasing spectra of the two structures shown in Figs. 23(b) and 24(b) reveal lasing frequencies of 2.7 THz and 4.1 THz, respectively. On the one hand, the agreement of the lasing frequencies with the position of the calculated gain maxima demonstrates that the model is applicable for the evaluation of THz structures. On the other hand, the rather large gain regions (about 0.5 THz), show that the model is still not sufficiently precise for a determination of the lasing frequency.

Figure 25 shows the threshold current density j_{th} of structure I as a function of temperature T . The maximum operating temperature T_{max} for structure I is 50 K, while structure II shows lasing up to 60 K. A comparison with the values reported by S. Barbieri shows that, although structure I has the lower j_{th} at 4.2 K (75 vs. 105 A/cm²), T_{max} does not reach the value of 95 K as reported in the literature. Probably, the heat management of the lasers affects the lasing properties of THz QCLs, for which the emission energy is similar to the thermal energy, to a significantly larger extent than for mid-infrared QCLs.

In order to obtain more information, the dependence of light output (L) on the current density (j) was investigated for several temperatures as shown in Fig. 26. The L - j characteristics clearly exhibit a maximum, for which also an indication of negative differential conductance is observed in the I - V characteristics. This behavior, which we also observed for mid-infrared QCLs operating at low field strengths, may provide an explanation for the rather low T_{max} of the THz QCLs. Obviously, the decrease of the gain with increasing temperature cannot be sufficiently compensated by a higher j , when $j > j_{max} \approx 150$ A/cm². Therefore, the design of THz lasers with monotonous L - j characteristics may contribute to the increase of T_{max} .

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